

NEUTRON RADIOGRAPHY

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NEUTRON RADIOGRAPHY

Pictures made by slow neutrons disclose many things that cannot easily be seen in pictures made by X rays. New detection methods are making it attractive to use neutrons as an inspection tool

by Harold Berger

The value of radiography in medicine and industry is so firmly established that today the amount of photosensitive film used for making X-ray pictures greatly exceeds the amount of black-and-white film used by amateur photographers. With X rays of sufficient energy and intensity it is possible to make pictures through objects of any material and of almost any thickness. It has been known virtually from the time the neutron was discovered, 30 years ago, that neutrons might also be used to make pictures through objects. But since neutrons in a form useful for imaging purposes are harder to produce than X rays, one may wonder what advantage is to be gained by making neu-

tron radiographs. The answer is that neutrons make it possible to see things that X rays do not reveal at all, or reveal only with difficulty.

Neutron radiography has become practical with the advent of nuclear reactors and particle accelerators, which can provide a source of neutrons of the required intensity. Nuclear reactors produce neutrons directly, as a by-product of nuclear fission. Accelerators produce beams of high-energy charged particles, usually protons, which can give rise to neutrons if they are directed against a suitable target material, such as lithium or beryllium. The high-energy neutrons produced by an accelerator are absorbed about equally by different materials. To

be most useful in radiography neutrons must be slowed down until their velocity is simply the velocity imparted to them by the random movement of atoms at ordinary temperatures. Such low-energy neutrons, called thermal neutrons, can be obtained directly from nuclear reactors.

The value of thermal neutrons in radiography is that their absorption characteristics are quite different from those of X rays. For elements at either end of the periodic table the absorption characteristics of thermal neutrons and X rays are essentially reversed [*see illustration on next two pages*]. Heavy elements such as lead, bismuth and uranium are practically transparent to thermal neutrons,



NEUTRON RADIOGRAPH OF GRASSHOPPER gives information that would be difficult to obtain in an X-ray picture. Tissue com-

ponents absorb X rays about equally. Neutrons, however, are heavily absorbed by hydrogen. Thus white areas here are hydrogen-rich.

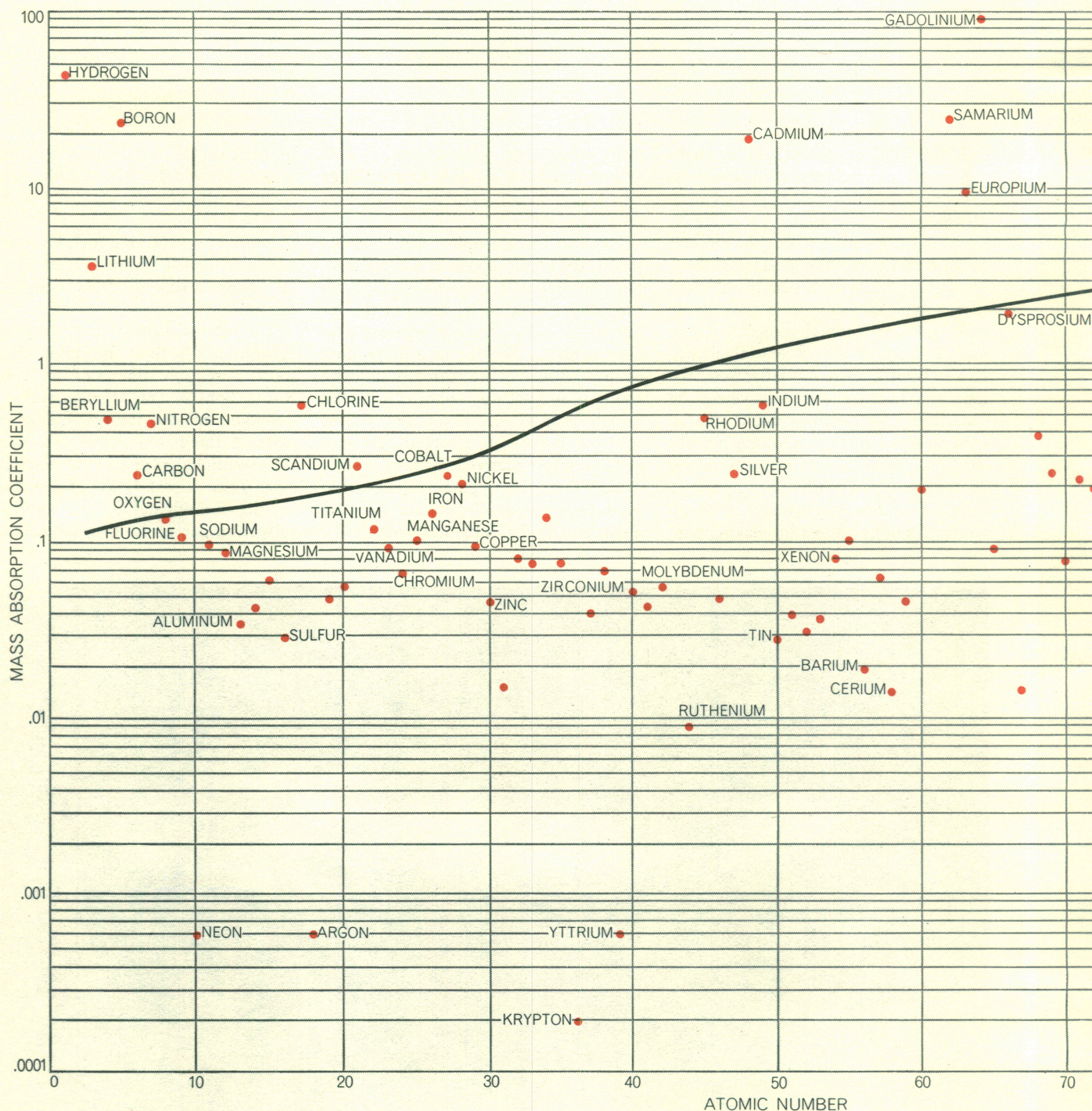
whereas they absorb X radiation strongly. Conversely, hydrogen, lithium, boron and other light elements strongly absorb thermal neutrons but allow X rays to pass freely. For example, with neutron radiography it would be an easy matter to record the height of a column of water in a lead tube. Neutrons would have no difficulty penetrating the lead but would be strongly absorbed by the hydrogen in the water. X rays would be so readily

absorbed by the lead that the slight additional absorption due to water would be difficult to observe.

In general, various materials stop X rays in direct proportion to their mass. For this reason it is difficult to distinguish between elements that lie near each other on the periodic table. Neutron absorption, on the other hand, is not related directly to atomic number or mass; neighboring elements such as cad-

mium and tin or boron and carbon can differ in neutron "transparency" by factors of 100 or 1,000.

A neutron radiograph is made in much the same way as an X radiograph. The object to be inspected is simply placed between a source of radiation and a radiation detector. If the source produces fast neutrons, they can be slowed down by allowing them to diffuse through a medium containing light elements, such



ABSORPTION CAPACITY OF ELEMENTS is plotted for X rays (black curve) and for thermal, or low-energy, neutrons (colored dots). The higher the mass-absorption coefficient, the more absorb-

ing the material. In general the coefficient for X rays increases steadily with atomic number. The coefficient for neutrons is much more random, but there is a tendency for absorption to be the

as hydrogen or carbon. Since a great many fast neutrons are absorbed in the thermalizing process, the original source must produce on the order of 10 billion neutrons per second to yield a thermal-neutron beam of useful intensity. We have found at the Argonne National Laboratory that an intensity of at least 100,000 thermal neutrons per square centimeter per second appears desirable. Even low-power reactors, however, can

produce beams 100 times more intense.

A number of commercially available accelerators can produce thermal-neutron beams of adequate intensity at a price competitive with high-energy X-ray equipment. Recently Edward J. Hennelly of the Savannah River Laboratory operated by E. I. du Pont de Nemours and Company has described a low-cost radioactive source of thermal neutrons. The source consists of radioactive antimony 124, which has a half life of 60 days, and beryllium. Neutrons are produced when the beryllium atoms are struck by gamma rays from the antimony 124. The initial cost of the source has been estimated at \$3,500, and the cost of maintaining the source at a high output should be less than \$5,000 a year.

One problem associated with fast-neutron sources is that the thermalized neutron beam also contains high-intensity gamma radiation. If the neutron beam were being used to inspect uranium or some other heavy metal, the gamma rays might even contribute usefully to the image. In other cases, however, gamma radiation may confuse the radiographic picture. One answer to the problem is to remove the gamma rays by means of a filter, consisting of an element such as bismuth, that has high absorption for gamma radiation but low absorption for thermal neutrons. Another approach is to allow the neutrons to strike a crystal and form a reflected beam that contains thermal neutrons but little or no gamma radiation. Such an arrangement is called a neutron spectrometer; it not only reduces gamma rays but also fractionates the neutrons into beams of different energies, or wavelengths. By selecting only neutrons reflected at a certain angle one can obtain a "monochromatic" beam in which all the neutrons have about the same energy. It happens that most of our radiographic studies at Argonne have been done with monochromatic beams, but such beams offer no advantage for most applications.

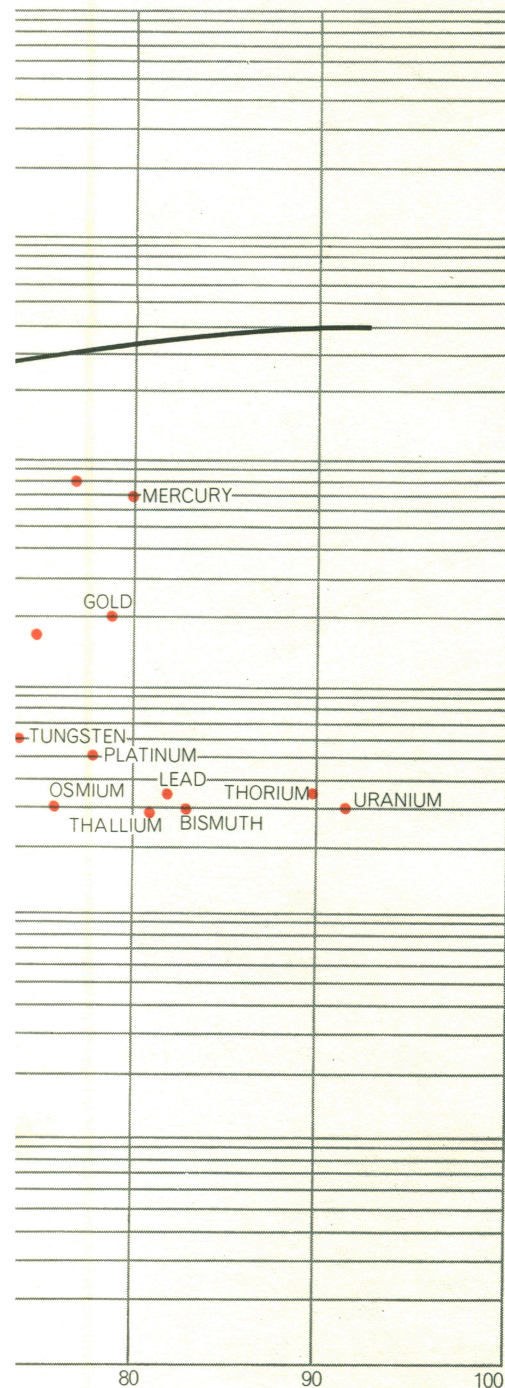
Still another way to combat the problem of gamma-ray contamination is to use detectors that do not respond to gamma rays. I shall therefore broadly describe the various methods of detecting neutrons. In the transfer method the neutrons are allowed to strike a metal screen that becomes radioactive in proportion to the intensity of the neutrons at each point. The screen thus contains a radioactive image of the test object. To make this image visible the screen is placed against photographic film, and the radiation arising from radioactive decay exposes the film. Since the photographic film is not exposed to the neutron

beam itself, the gamma rays in the neutron beam are made ineffective.

Metal screens for the transfer method incorporate isotopes that have a conveniently short half life. Examples are gold 198 (half life, 2.7 days), dysprosium 165 (2.3 hours), indium 116 (54 minutes), rhodium 104 (4.4 minutes) and silver 108 (2.3 minutes). Even with saturation exposure the Argonne neutron beam with an intensity of 100,000 neutrons per square centimeter per second yields a barely detectable transfer image when short-lived rhodium and silver are used in conjunction with a fast X-ray film. The image cannot be strengthened by lengthening the exposure because after a certain time—equal to about three half lives of the isotope in the screen—the number of atoms decaying begin to match the number of new radioactive atoms being produced. To achieve a stronger image with very short-lived isotopes it is necessary to increase the intensity of the neutron beam. As it is increased more radioactive atoms are created per unit of exposure time, and the level of radioactivity in the screen is increased correspondingly. As a result rhodium and silver isotopes, as well as many others, can be used to make transfer radiographs with beams that have an intensity greater than 100,000 neutrons per square centimeter per second.

Another neutron-detection method can employ a wide range of screen materials, including some that do not actually become radioactive; it also responds, however, to the gamma radiation in the beam. In this technique, which we have termed the direct-exposure method, the screen and the film are exposed to the neutron beam together. The neutrons have little direct effect on the film, but the film now accumulates all the radiation emitted from the screen during the exposure. In addition to collecting all the radioactive-decay radiation, the screen also collects "prompt emission" radiation, which can consist of either gamma rays or charged particles (usually alpha particles, or helium nuclei) produced almost instantaneously by neutron bombardment. This prompt emission combines with the decay emission to allow much shorter exposures with the direct-exposure method than with the transfer method.

Several materials that have only a negligible tendency to become radioactive make excellent direct-exposure screens. These materials include cadmium and gadolinium, which are prompt gamma-emitters, and certain isotopes of boron and lithium that emit alpha particles when they are struck by slow neu-



reverse of that for X rays. Values are based on those given by James Thewlis of the Atomic Research Establishment at Harwell.



"JUGGERNAUT" RESEARCH REACTOR at the Argonne National Laboratory provides an intense beam of neutrons useful for radiography. The beam leaves the reactor through a slot opposite

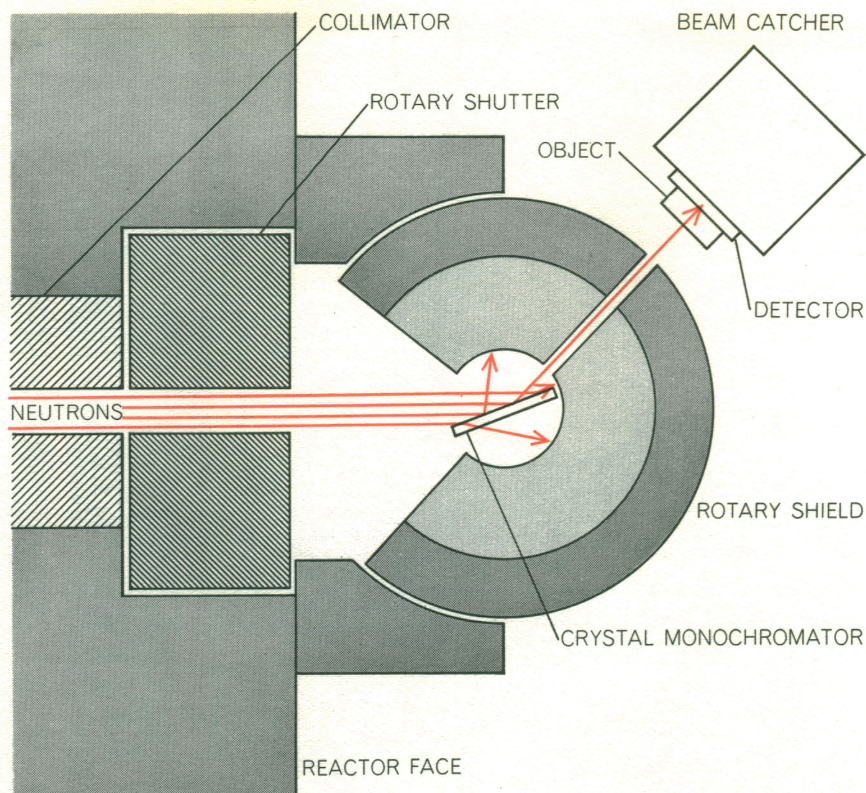
the horizontal cylinder. The object to be radiographed is mounted in front of the cylinder, which stops the beam. A close-up of the cylinder and the neutron exit port appears at the top of page 8.

trons. The most sensitive detectors are made by combining the alpha-emitters boron 10 and lithium 6 with a phosphor, such as silver-activated zinc sulfide, which gives off flashes of light when it is struck by alpha particles. These scintillations expose the film more effectively than alpha particles themselves do. Such detectors produce good images when struck by only a few hundred neutrons per square millimeter. This is at least an order of magnitude more sensitive than any other neutron detector that seems useful for radiography.

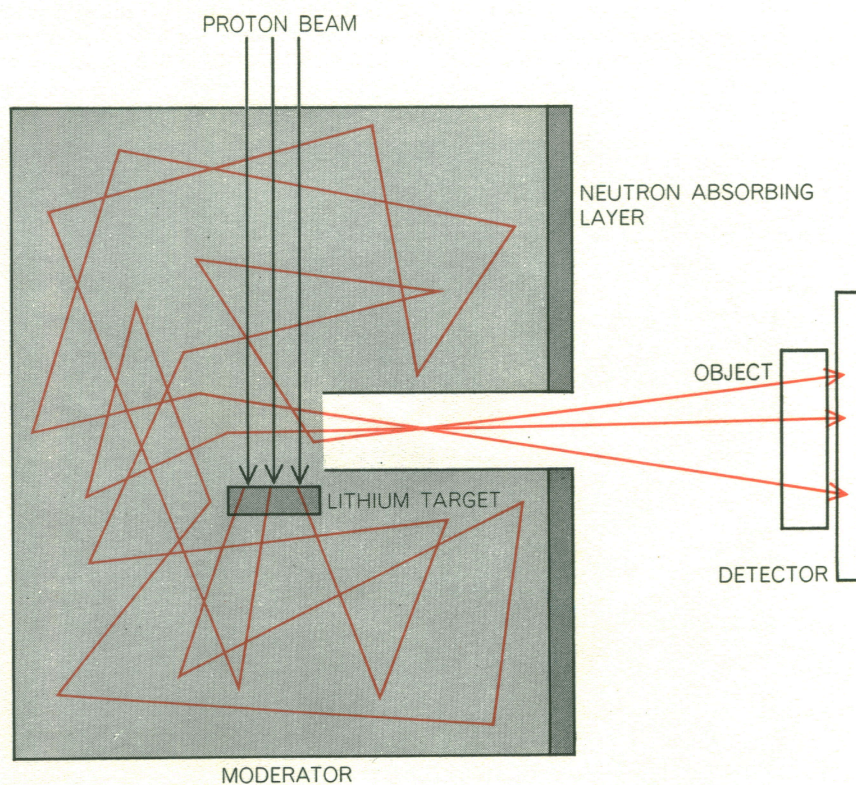
The over-all sensitivity of the detector depends, of course, on the speed of the film employed. Until recently the shortest exposures were obtained with scintillators placed in direct contact with blue-sensitive X-ray films, such as Kodak Type F, or with the Polaroid film that has a speed rating of 3,000. The newly available Polaroid film with a rating of 10,000 has cut exposure times still further. It is possible to detect neutrons directly in ordinary photographic film, without the need for screens, and one can also use special emulsions loaded with boron 10 or other elements that produce radiation when struck by neutrons, but the speeds are still below those obtainable by converter-screen methods,

The various detection methods differ not only in speed but also in image sharpness. To examine sharpness, or resolving power, we have made many neutron radiographs of test objects containing small holes. We find the highest resolution is obtained with thin gadolinium screens in a direct-exposure method. Test films made by this method produced distinct images of tiny holes that are appreciably closer than 1,000th of an inch. The sharpness can evidently be attributed to the fact that gadolinium, when struck by thermal neutrons, emits low-energy electrons that travel only a short distance in the photographic emulsion. Next in order of image sharpness are most of the transfer methods and the direct exposures using scintillators. Other direct-exposure methods, using screens of such materials as cadmium, silver and indium, yield somewhat poorer images.

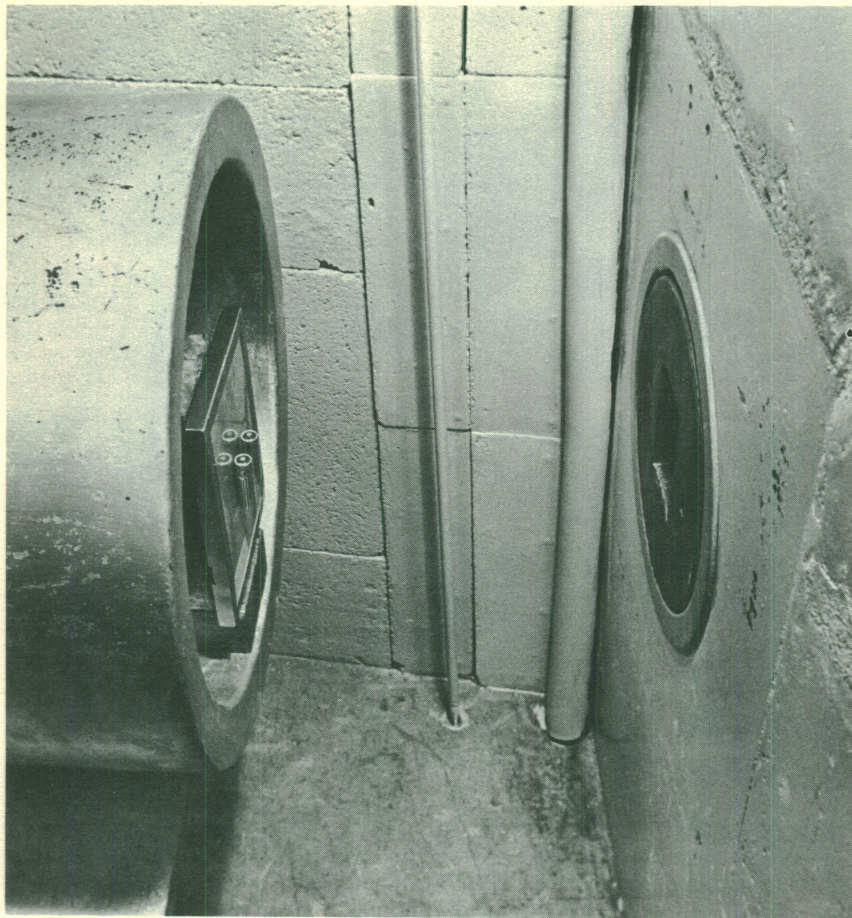
Another important property of a radiographic image is contrast, which makes it possible to distinguish different thicknesses of material in the test object. In examining the heavy metals, for example, we find that we can usually detect thickness variations of the order of 1 per cent with any of the detection methods, except when a scintillator is employed. In



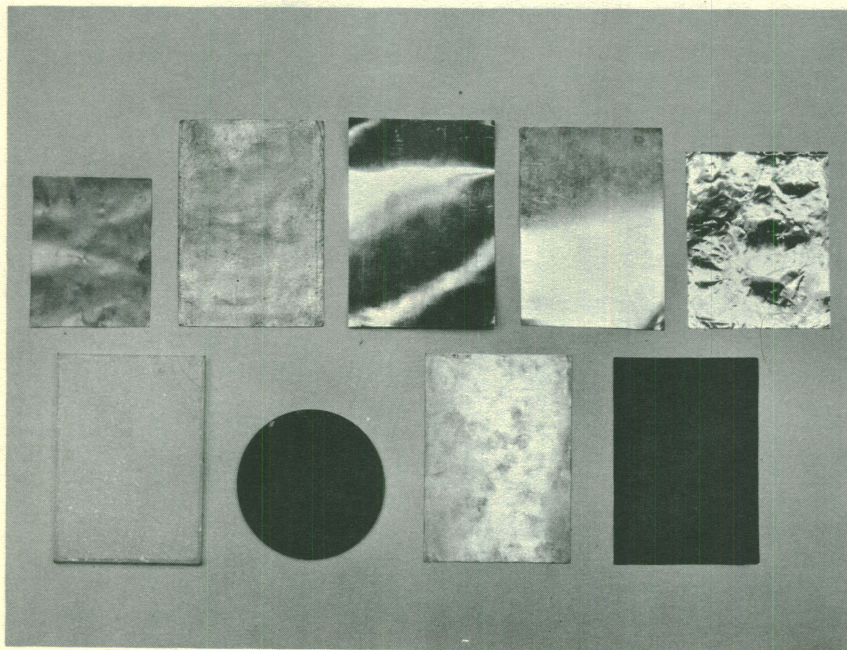
REACTOR NEUTRON SOURCE is of the type used by the author in experiments at the Argonne National Laboratory. After leaving the reactor (*left*) the neutrons strike a large single crystal, where they are deflected at various angles depending on their energies. For most radiographic purposes the neutron beam could be used just as it leaves the reactor.



ACCELERATOR NEUTRON SOURCE yields high-speed neutrons when high-energy protons strike lithium or some other suitable target. The neutrons are slowed down by diffusing through a moderator, which contains light elements such as hydrogen or carbon.



SETUP FOR NEUTRON RADIOGRAPHY is demonstrated at the Argonne National Laboratory. The neutron beam emerges from the Juggernaut reactor through the port at the right. Objects to be examined (small dry batteries) are mounted on a detector screen. Neutron radiographs of the batteries are compared with X radiographs at bottom of page 10.



RADIOGRAPHIC SCREENS convert neutron radiation into radiation that exposes photographic film. When struck by neutrons, the screens in the top row (dysprosium, indium, rhodium, silver and gold) become radioactive; the two screens at right in the bottom row (cadmium, gadolinium) emit gamma rays; the other two (boron scintillators) give off light.

images produced by a scintillator the smallest detectable thickness variation runs from about 5 to 15 per cent. Although the scintillator methods leave something to be desired, we have found them useful for a quick look at a new test object. Speed and convenience are particularly good when the scintillator image is recorded on the high-speed Polaroid film, which develops in only 10 seconds.

Generally speaking, the resolution and contrast of the better radiographic methods compare favorably with those commonly obtained with conventional X-ray and gamma-ray equipment, but they do not yet measure up to the best results obtainable with X rays. Nevertheless, the quality of present neutron radiographic methods is high enough to suggest many industrial and technical applications, particularly where neutrons can provide distinctive information.

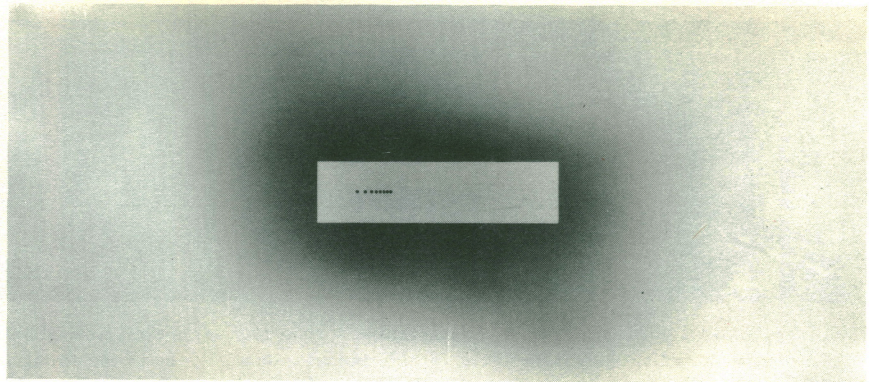
In metallurgy, for example, neutron radiography could be used to observe concentrations of light elements such as hydrogen, lithium or boron contained within various kinds of materials or objects. The top illustration on page 10 is a neutron radiograph of a zirconium bar containing sintered boron carbide, used to control the neutron intensity in portions of a nuclear reactor. A critical component in the bar is boron, placed there because of its capacity for absorbing neutrons. One would like to have an inspection method that would show whether or not the boron is distributed uniformly. An X radiograph is not much help because boron carbide and zirconium absorb X rays about equally. Neutrons, however, are absorbed several hundred times more readily by boron than they are by zirconium; thus the distribution of the boron shows up clearly in a neutron radiograph. Going through the periodic table, one can find many other combinations of substances that are easily distinguished by neutron absorption but not by X-ray absorption.

Another metallurgical use for neutron radiography is in the inspection of objects containing heavy metals such as uranium, lead and bismuth, which are much more transparent to neutrons than they are to X rays. When the thickness of such metals runs beyond a few inches, the exposure time for a neutron radiograph can become significantly less than for an X radiograph [see illustration on page 9]. Even the low-intensity neutron beam at Argonne can be used, with high-resolution techniques, to inspect a sample of uranium two inches thick in about an hour. This is only a small fraction of the comparable exposure that

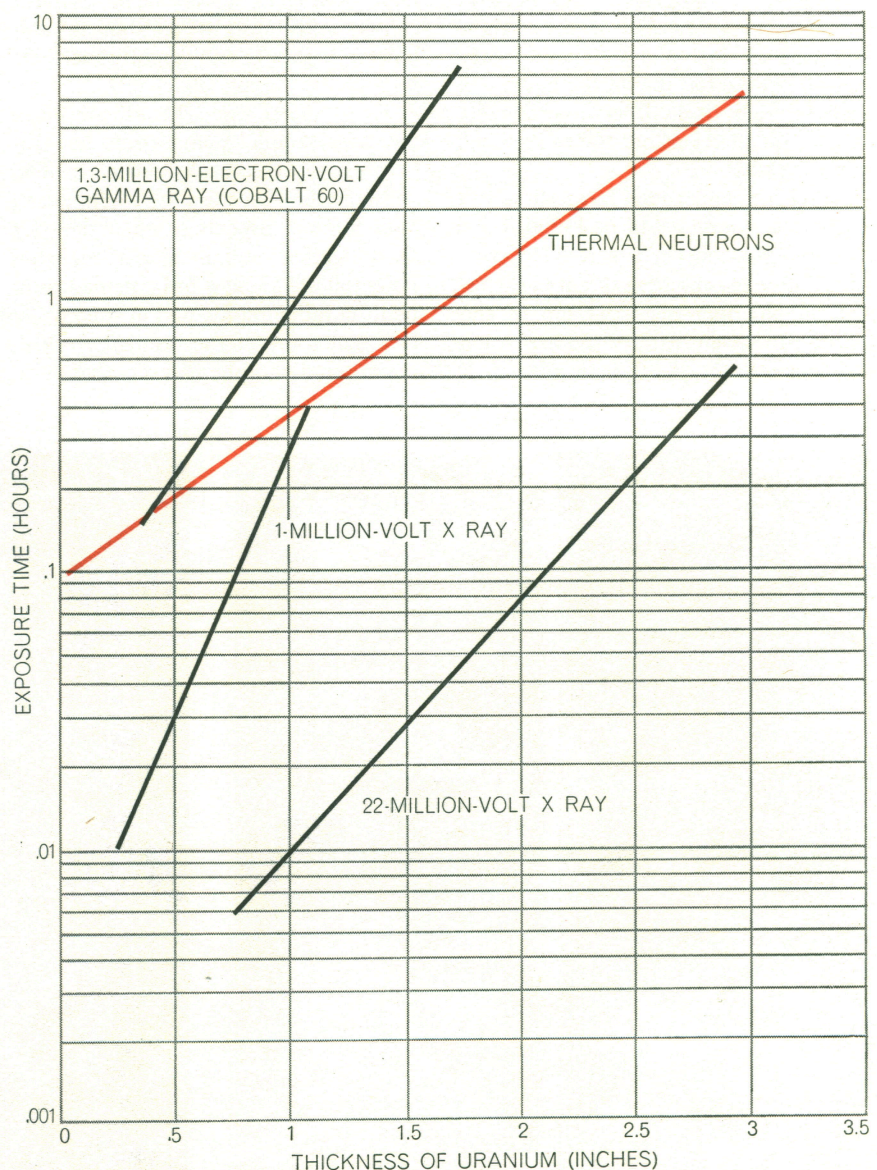
would be required with a standard one-million-volt X-ray generator or with gamma rays from a cobalt-60 source of fair intensity. With neutron beams of greater intensity than our original Argonne beam, which should not be difficult to achieve, the exposure time could be cut to less than a minute. In comparison, the 22-billion-volt X rays from a betatron would require several minutes to produce a comparable radiograph through two inches of uranium. Actually with the fast scintillator technique the Argonne beam could produce a neutron radiograph of such a sample in less than 30 seconds, but the quality of the picture, as I have explained, would be substantially below X-ray quality.

One of the fascinating things about thermal neutrons is that the same neutron beam used to inspect several inches of uranium or lead can be used to inspect specimens such as leaves, insects and thinner biological specimens. The neutron picture of a grasshopper on page 3 illustrates the possibility of applying neutron radiography in biological studies. I do not mean to suggest that neutron radiography of living animals or humans is feasible, much less desirable. Quite the contrary; the rich hydrogen content of animal tissue would make it difficult for the neutron beam to penetrate, and the exposures needed might induce enough radioactivity in the tissue to harm the organism. Neutron inspection of thin biological specimens may nonetheless offer advantages, particularly if the purpose of the inspection is to locate the position of hydrogen or other neutron-absorbing materials. For such biological applications the exposures required for neutron radiography are not excessive. With the use of metal screens and fast X-ray films, a radiograph of reasonable quality can be obtained with a total exposure of 10 million thermal neutrons per square centimeter of detector. This can be translated into an exposure of about 10 milliroentgens, a figure comparable to that required by fast X-radiographic methods.

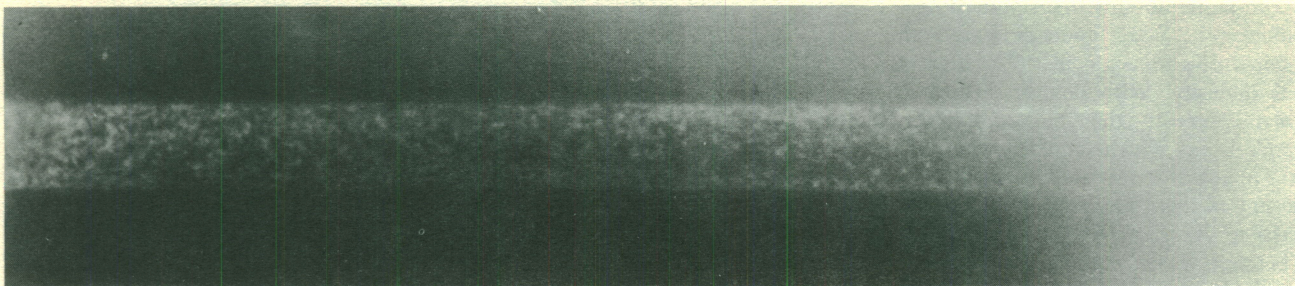
The strong neutron absorption of hydrogen also makes inviting the possibility of neutron-radiographic inspection of such hydrogen-containing materials as paper, rubber, wood, plastics and adhesives. Small differences in the hydrogen content or the thickness of such substances, as well as the location of the substances in objects primarily made up of other materials, should be comparatively easy to observe with neutron radiography. The radiographs of the small batteries at the bottom of page 10 show



RESOLUTION TEST shows that neutron radiography can record fine detail. The test object is a piece of cadmium containing eight holes .02 inch in diameter. The picture was made with a thin gadolinium screen by the direct-exposure method described in text. The irregular blackened area around the object shows the actual dimensions of the neutron beam.



RADIOGRAPHIC EXPOSURE TIMES are shown for neutrons, for gamma rays from cobalt 60 and for X rays of two levels of energy. Gamma rays and X rays, of course, are both high-energy photons and carry different names only by custom. Exposure times reflect typical values for X-ray and gamma-ray sources and are based on the work of Gerold H. Tenney of the Los Alamos Scientific Laboratory. Neutron exposures are for an intensity of 100,000 neutrons per square centimeter per second, using a gadolinium screen and direct exposure.



ZIRCONIUM BAR containing boron carbide makes a good test object for neutron radiography. Since boron carbide and zirconium have about the same absorption for X rays, an X radiograph would

not tell much about boron carbide distribution. Boron, however, is one of the strongest absorbers of neutrons, whereas zirconium is only an average absorber. Hence boron carbide shows up as white.

the different responses of neutrons and X rays to objects containing various substances, including hydrogen. The pictures are X radiographs and neutron radiographs of new and used batteries. One can see first of all that the waxy material in the top seal of the battery—a material rich in hydrogen—completely absorbs the neutrons but transmits much of the X radiation.

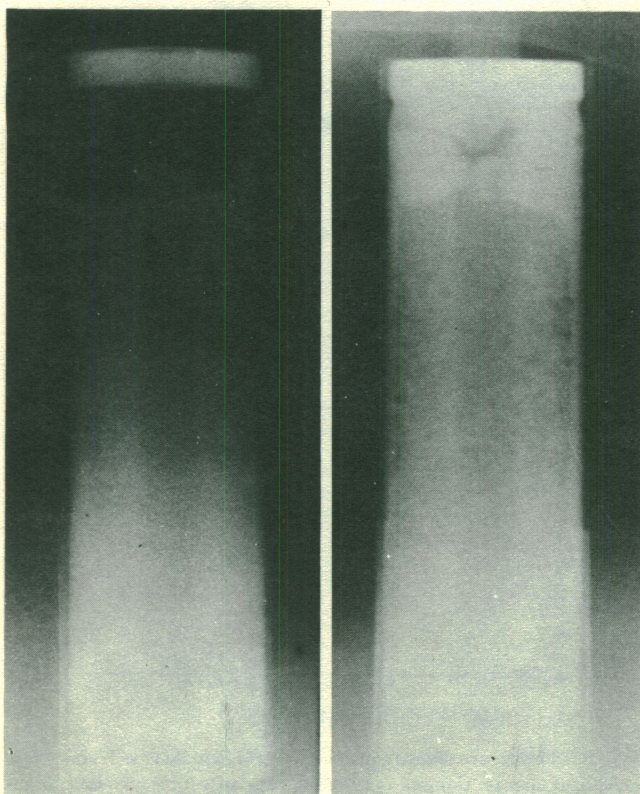
A second and more interesting difference in response can be found if one compares the new and the used batteries. This difference is most evident in the expansion chamber near the top of the battery. In a new battery the expansion chamber is empty; both neutrons and X

rays pass through it easily. In a used battery the expansion chamber has become filled with a paste-like material of high hydrogen content. The material consequently absorbs neutrons strongly but for X rays is only slightly more absorbent than empty space.

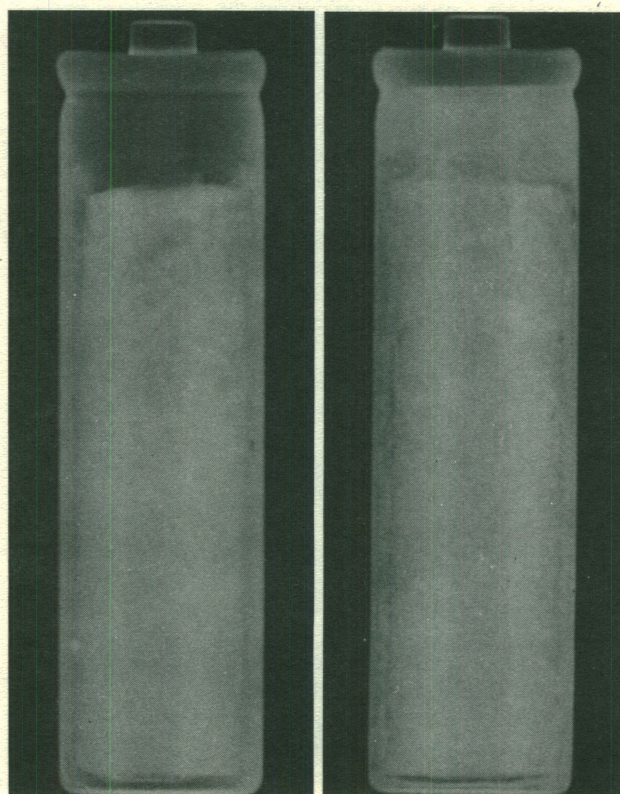
These neutron and X radiographs of the same samples demonstrate how the two techniques complement each other and how they broaden the usefulness of radiographic inspection when they are used together. Still, in spite of the many potential advantages to be gained using neutron radiography, and in spite of the fact that some of the original work on neutron radiography was reported in the

technical literature more than 15 years ago, little use has been made of this inspection method to date.

This is perhaps not too surprising; the availability of neutron sources that have characteristics useful for radiography is still not very great. It is also true that until recently the quality of inspection possible with neutron radiography was not widely known, nor was much known about the many useful detection methods that could be employed for neutron imaging. As a result anyone wishing to try neutron radiography for a special inspection problem had the task of finding suitable equipment and of working out his own exposure methods. Even now,



RADIOGRAPHS OF SMALL DRY BATTERIES were made with neutrons (pair at left) and X rays (pair at right). In each set of pictures the battery on the right is a used one, hence the expan-



sion chamber near the top is filled with an ammonia-containing material. This material produces a strong increase in neutron absorption but only a modest increase in X-ray absorption.

with many of these difficulties much diminished, there are still problems standing in the way of the routine application of neutron radiography.

In order to inspect large objects, or to view many small objects in one exposure, it would be desirable to have a larger beam of radiation than any now available. Most of our experiments were done with a neutron beam that covered an area only about three inches in diameter. The beam from the recently completed Juggernaut reactor at Argonne, shown on page 6, will produce radiographs 2.5 by four inches and will eventually sup-

ply a neutron beam six inches in diameter. It is possible, of course, to radiograph large objects section by section with small beams, but obviously this is slow and cumbersome. In short, the difficulty of obtaining large, uniform neutron beams of high intensity is still a major deterrent to the widespread application of neutron radiography.

For many purposes, particularly scientific ones, it would also be valuable to have a well-defined diverging beam of neutrons. Such a beam would in effect constitute a neutron microscope. It could be used, for example, to observe hydride

precipitation in single crystals of metal or to observe the diffusion of boron or lithium in semiconductor materials. A diverging neutron beam would also have many uses in biology.

Better neutron sources are therefore needed to help neutron radiography realize its full potential. Even now, however, the capabilities and potential advantages of neutron radiography recommend its consideration for a variety of inspection problems. There is not much doubt that it will eventually become a routine inspection tool.

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